A Geophysical Sudy of Landslides (Applicaion of the Elecrical Resistivity Survey to Landslides)

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Abstract

The author has carried out surveys at various landslide areas utlising the electrical resistivity method. From the results, it has been clarified that soil movement in areas of tertiary formation is caused within the range of resistivity values of 0.8~5.2 kΩ-cm. However, it is not only one slide layer that moves when a landslide is to take place but any other part or parts within one slide surface that can move under any predisposing conditions.

The low apparent resistivity values according to the distribution map in landslide areas determined by the horizontal exploration using the resistivity method or what we call the method of the same electrode spans considered to be a locality containing underground water if in these landslide areas soil movement has occurred rapidly, or a locality having a high possibility of landslide soil movement taking place in future if these low apparent resistivity areas have continued soil movement or soil movement.

1. Introduction

Needless to say it is a prerequisite of conducting a land survey to examine the underground geological structure. For this purpose geological surveys and boring surveys have been put into practice. Such studies as were necessary to find the order of the underground geology, so that we can distinguish one kind of soil layer that is likely to slide from the order kinds that are not likely to slide, have been carried out. Other kinds studies to determine the depths of layers by means of boring surveys by finding the existence of any clay layer and its softness have also been pursued. The joint use of these two kinds of studies are now throwing new light on the relationships between the underground geological structure and the position of any slide surface.

It has been made clear [1) 2)] that it is necessary to provide several bore holes at one place in order to have a good knowledge of the position of one slide surface and moreover that it is necessary to conduct an extensive boring survey at a great number of different places in order to be able to estimate the position of any slide surface in one landslide area as a whole. The reason is because a survey that is based on one boring hole can not be free from a defect which makes it impossible to make an estimation of a full-scale underground structure.

Momose [3)] and Yamada [4)] conducted a survey to examine the underground structure of a landslide area by adopting the electrical resistivity method. But, since no boring survey was carried out in that particular area, they had in fact no way to check the estimated depth of the slide surface against the actual depth of the bed rock. Nevertheless, because it was clear that it was possible to obtain some knowledge of the underground geological structure if the electrical resistivity method was applied, this method came to be put into frequent use at various other places. In addition this method had the distinct and twofold advantages that it could obtain the necessary results in a short period of time and that it required less cost in making a necessary survey. Yet, when the Symposium of Landslide Surveys was held some fifteen years ago, the conclusion was then reached that it was impossible to make an exact determination of the position of any slide surface or the depth of any bed rock using the electrical resistivity method [5]. The reason for such a conclusion seems to have been the wrong application of the electrical resistivity method to those landslide areas to which its theoretical assumption was not applicable and partly because of the hasty, sometimes unreasonable, estimation of the slide surface. Naturally, this method came to be no longer used in any landslide as a result.

However, the present writer, wondering why this speedy and inexpensive method of conducting a survey should have been disregarded, has been making efforts to restore the use of this method for landslide surveys. Under such circumstances the present writer attempted to conduct an electrical resistivity survey in particular landslide areas for which all the necessary geological data of the underground geological structure had already been clarified by a number of boring surveys, with the particular intention of (1) finding the reason why the results of this method didn't conform with the other actual results and (2) trying to determine the limitations of the electrical resistivity method, if any.

As a result it was found that the electrical resistivity method was a very useful means applicable to any landslide area in order to determine the underground geological structure as far as it was adequately applied, and as results of a great number of the electrical resistivity surveys conducted at a variety of landslide areas have shown, the extent of its applicability has come to be windened not only to the slide surface and the bed rock depth, but also to some other purposes.

2. Applicability of the electrical resistivity survey to a landslide

In order to determine the applicability of the electrical resistivity method to a landslide survey this method must be used at such places for which complete data have made known and available. Now, fortunately the Tanokura landslide area located in Matsudai-cho in Niigata Prefecture happens to be a locality about which a variety of researches, such as boring and surface displacement surveys and slide surface study, had already been completed by Tsumoto [6], so that a complete synopsis of this landslide area has been provided and is available. For this reason the present writer chose this area as an experimental one for the electrical resistivity survey.

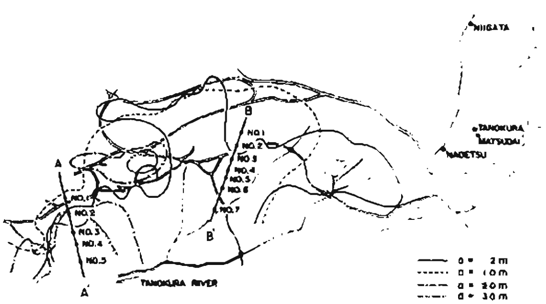

Fig. 1 The measuring location used in the resistivity survey and topography of the Tanokura landslide area

Wenner's four electrode system was adopted for the electrode arrangement and vertical explorations were conducted at such places where surveys of the geology or slide surfaces had already been made by of means boring. The landslide area of Tanokura, viewed geologically, was composed of an alternate layer of tuff and shale, and mud stone, all of which are of the Tertiary formation, the lowest layer of the Teradomari formation principally composing mud stone. Down to the depth of about 30 meters was an alternated layer of tuff and shale which had largely turned into clay and in some places solid massive rocks made of those elements were found.

The present writer compared the two different results obtained from these vertical explorations and from the boring surveys both conducted along the two measuring lines A-A' (Figure 2) and B-B' (Eigure 3). The easiest and simplest way to compare the resistivity layers with the geological section view is to examine the respective depths of each bed rock.

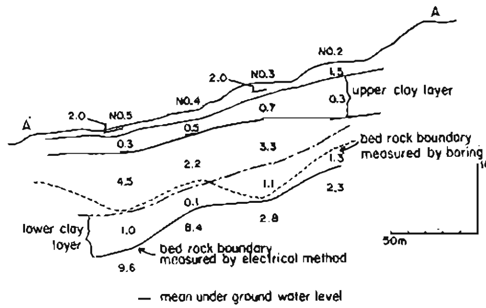

Fig. 2 The comparison between the underground structure estimated by boring survey and on the one estimated by resistivity survey at A-A' section

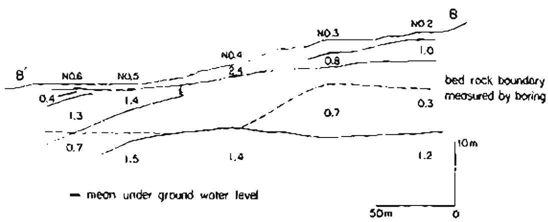

Fig. 3 The comparison between the underground structure estimated by boring survey and the one estimated by resistivity survey at B-B' section

According to my electrical resistivity survey, the resistivity layers of this particular landslide area were revealed to be a 3-4 layer composition. Upon the supposition that the is lowest layer must have been its bed rock, I compared it with the bed rock confirmed by the boring survey. Then it was found that the depth of the bed rock estimated by the electrical resistivity method showed that it was lying deeper in all cases than bed rock depth calculated by the boring survey, though including maximum errors of 7 meters.

These errors could well be accounted for by the fact that the analytical theory of a structure of multi-layers advanced on the basis of the concept of the equivalent layers of Hummel [7] and Ono [8] did not match the actual electrical underground composition of this landslide area.

The present writer thought that the theoretical assumption was by no means applicable because the geology of this landslide area must have been disarranged, naturally leading to the conclusion that it would be quite impossible to conduct an electrical resistivity survey in this landslide area. But I assured myself that as far as a layer having a relatively high resistivity value existed at the lowest bottom, a comparatively good result could be achieved. For example, the results of two different ways of approach in finding the depth of a bed rock, i.e., the electrical resistivity method at measuring point No. 2 in section A and No. 4 in section B on the one hand and the boring method on the other, were found to show exactly the same findings.

In addition, it was also found that the underground table was found to correspond to the boundary of the resistivity value as shown in Figures 2 and 3. However, it was imppossible to parallel the boundary of the geology with that of the resistivity layer.

On the other hand, Tsumoto[9] measured the depths of slide surfaces at boring holes located in the two sections A and B using measuring tubes of the slide surface, the results of which are shown in Table 1. Figures 4 and 5 show the

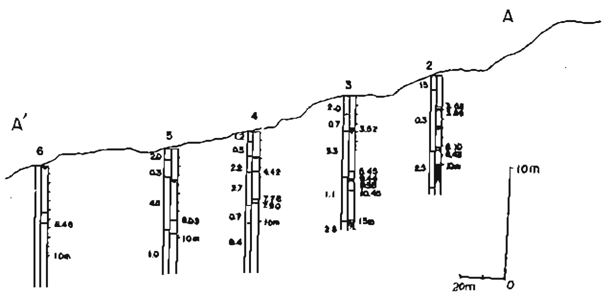

Fig. 4 The comparison between vertical resistivity distribution and depth of slide surface at A-A' Section, the figures of left side show resistivity values (KΩ-cm), right side show depth of slide surface

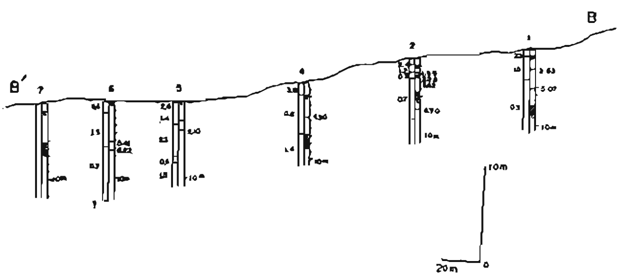

Fig. 5 The comparison between the vertical resistivity distribution and the depth of slide surface at B-B' section, the figures on left side show the resistivity values (KΩ-cm), right side the depth of slide surface.

comparision of the respective depths of the boundary of resistivity layers with those of the slide surfaces. In addition Table 2 shows resistivity values and individual numbers of slide surfaces within respective resistivity values. The following interesting facts came to our knowledge when Figures 4 and 5 were compared with Tables 1 and 2. That is, (1) in the layers having resistivity

Observation Points	No. 2		No. 3		No. 4		No. 5		No. 6	
	A	B	A	B	A	B	A	B	A	B
'59 Apl.	3.86		3.52							
			9.44							
May.	3.86		3.45							
			9.55							
June.	3.86		9.55	2.28						
July.	3.86		9.55							
Aug.	3.86	2.63	9.55							
Sep.	3.86	5.09	9.55		4.42					
Oct.	4.13		4.42	1.99	4.43	4.50				
	8.45		8.45							
			10.45							
Nov.	3.60		3.51	2.42	4.43			3.78	6.45	6.22
	8.10		9.45		7.90					
Dec.	3.67		3.56	6.69	7.78		8.03	3.78	6.40	5.41
			4.24	1.99						
			13.16							

A : shows A-A′ section B : shows B-B′ section

Table-1 The depths of slide surface which were estimated by the cylinder in tube at the Tanokura landslide area

resistivity (KΩ-cm)	0.3	0.6	0.7	0.8	1.1	1.3	1.4	1.2	2.3	3.3
number of slide surface	10	1	3	3	10	1	1	3	1	2

Table-2 Frequency of slide surfaces in various layers which have different electric resistance value

place	geology of slide layer	resistivity value of the layer		landslide type
Tanokura	tuffecous clay	0.3	4.5	tertiary type
Matsunoyama	brecciaed tuff	1.2	4.7	〃
Mikage	shilty clay	0.9	5.1	〃
Soryo	lomay clay, clay	0.8	4.5	〃
Kushibayashi	clay	1.2	4.2	〃
Choja	weathed serpentine	10	20	fracture type

Table-3 The relation betwee geology of slide layer and resistivity value which was obtained by vertical exploration. (unit KΩ-cm)

values 0.3~4.5 kΩ-cm many slide surfaces were observed and in those having resistivity values 0.1~1.1 kΩ-cm ten individual slide surfaces were observed in

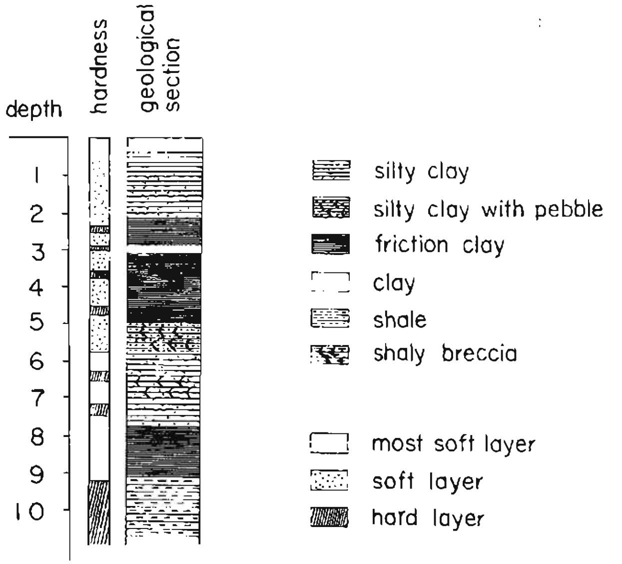

Fig. 6 The geological section at the Tanokura landslide area

each case ; (2) the number of the slide surface, of which the depths observed were somewhere near the boundary of the resistivity values amounted to as many as 19 individual places out of the total number of 26 places, the fact of which shows that the slide surface did have something to do with the boundary of the resistivity values. Consequently, if the soil mass movement could be regarded not as a slide surface but as a slide layer, then the resistivity value of the slide layer in this landslide area should have been 0.8-5 kΩ-cm.

When the assumed bed rock obtained by the electrical resistivity method was compared with the calculated bed rock found by the boring survey, the resistivity value of the layer which was supposed to be the bed rock turned out to be 1.4-8.4 kΩ-cm. On the other hand, since the resistivity value of the slide layer should have been 0.8-5kΩ-cm, it was impossible to find the bed rock from the resistivity value alone.

The fact that the boundary of the resistivity value happened to be observed more frequently somewhere near the slide surface made it deducible that there did exist some electrical difference between the moving layer and the stationary layer. Then it followed that since the bed rock should have been located beneath the slide surface, even if the bed rock in itself could not be estimated by the difference in resistivity values, the bed rock surface could be determined by estimating the slide layer from the resistivity values.

As for the perpendicularly discontinued layers in a given cross-section, some discontinuity or dislocation of the resistivity values was observed according to the result of the resistivity survey between No. 4 and No. 5 in section A : No. 4 and No. 5, and No. 6 and 7 in section B (Figure 7). According to the results of the boring survey it was accepted that the discontinuity in section A formed the boundary of the collapsed soil caused by a landslide in the past and that the discontinuity in section B was a geological dislocation (Figure 8). In this way it was possible to find any discontinued or dislocated place at any given cross-

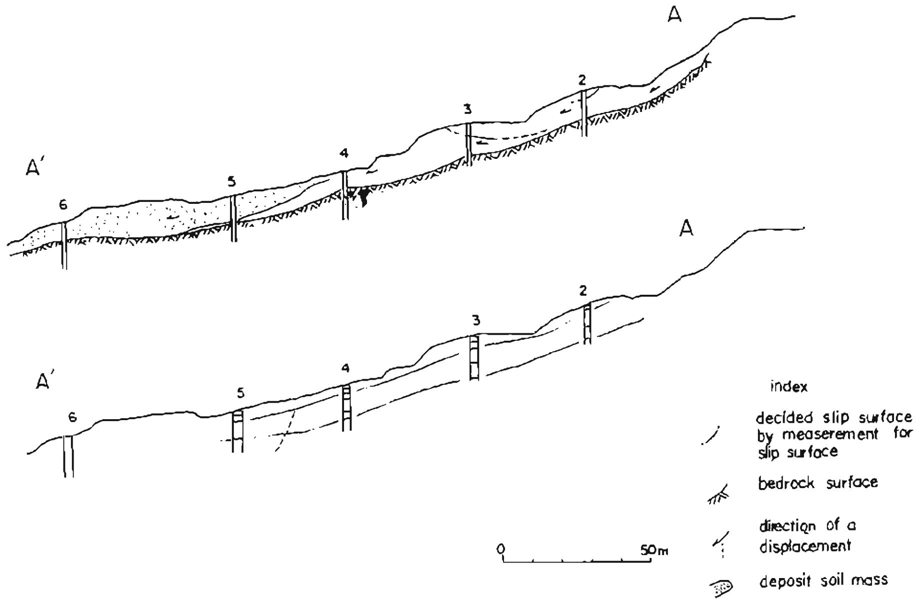

Fig. 7 The comparison between the underground structure estimted by resisti vity survey at A-A′ section

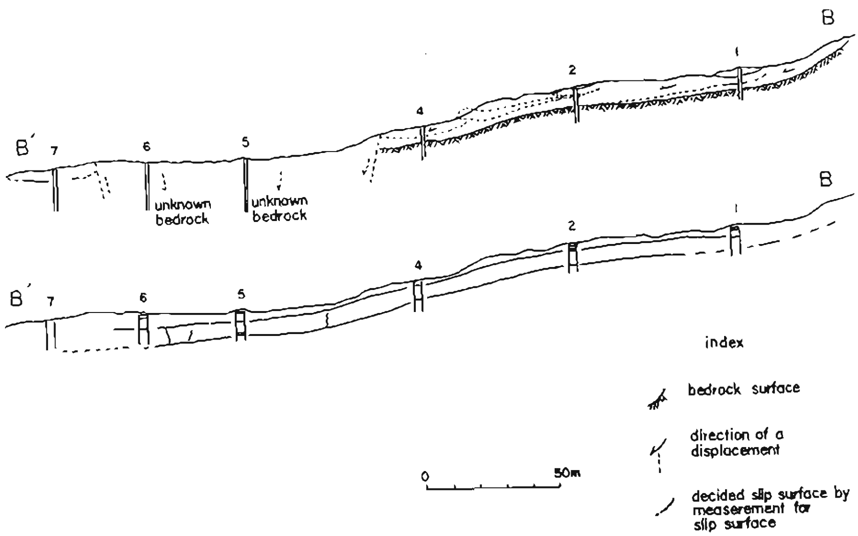

Fig. 8 The comparison between the underground structure estimated by boring survey, and the one estimated by resistivity survey at B-B′ section

section of any geological strocture using the electrical resistivity method, but it was impposible to know anything about the possible cause of any discontinued point of such dislocation without the assistance of the boring survey.

Since it was found that any soil layer likely to cause a landslide movement was characterized by rather low resistivity values when viewed electrically, the present writer as a next step proceeded to contemplate some means to represent superficially thc soil layer which was likely to cause the slide movement.

What is called the 'method of the same electrode span' is known as one of various methods of examining the geological structure horizontally. This method is being used these days as a supplementary means when the underground geological structure is to be determined by means of vertical exploration. When this method was applied to this landslide area, we obtained what is shown in Figure 9～12. While almost no difference was observed in the distribution of the low apparent resistivity values in the cases of the electrode span of 2 meters and 10 meters, theis distribution in the case of the electrode span of 20 meters was found to be concentrated in a certain area. Furthermore, when the electrode span was increased to 30 meters, low apparent resistivity values less than 2 kΩ-cm were observed to no longer exist.

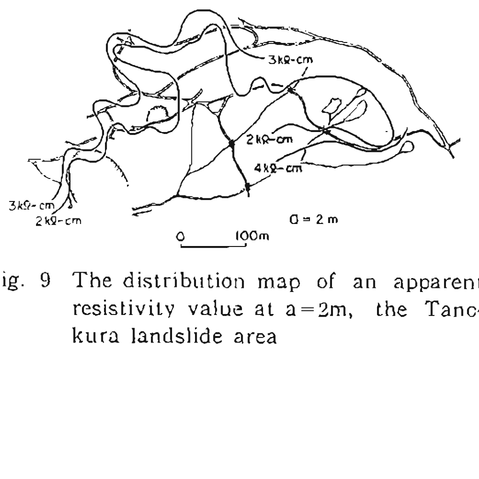

Fig. 9 The distribution map of an apparent resistivity value at a=2m, the Tanc-kura landslide area

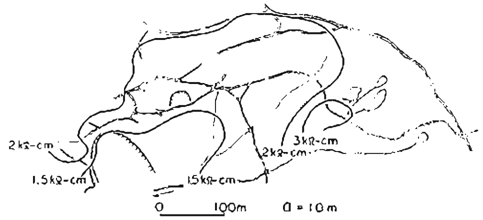

Fig. 10 The distribution map of an apparent resistivity value at a=10m, the Ta-nokura landslide area

In reference to the relationships between the distribution of the low apparent resistivity values and landslide happenings, the results obtained from our vertical explorations deserve special notice : i.e. The facts that (1) the slide mass soil is concentrated somewhere near the boundary of the resistivity values, (2) the slide layer has relatively low resistivity values and (3) the way the low apparent resistivity values are distributed in the case of the electrode span of 20 meters when the changes in resistivity values are caused by the ratio of the moisture content in clay, as pointed out by Yamaguchi [10], are taken into consideration. In other words it was possible to foretell that any area where the low apparent resistivity values were less than 2 kΩ-cm signified that (1) such an area should have abundant underground water, or (2) such an area should have the highest chance of causing a landslide movement because of the clayey nature of the soil mass due to the abundant underground water.

The foregoing is a description of

the surveys conducted in 1960, but on 12th April 1962 a landslide broke out at the place indicated by the hatched line shown in Figures 10-11. The depth of the slide surface was estimated to be somewhat less than 10 meters [11]. In the central part of this landslide area our measuring line A, was situated where we tried to survey the underground structure.

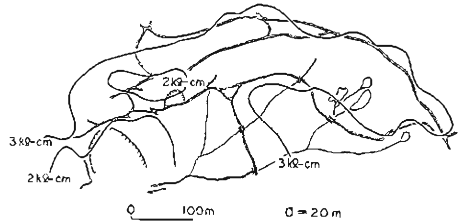

Fig. 11 The distribution map of an apparent resistivity value at a=20m, the Tano kura landslide area

Now, coming back to Figure 2 again, upon comparing the slide surface and the resistivity values obtained in 1960, it became clear that this landslide took place within the range of the resistivity layers of 1. 1-4. 5 kΩ-cm. In this way we found that the electrical resistivity method as one of varied kinds of researches could adequately be adopted for landslide surveys. The results obtained at the Tanokura landslide area by this method may be summarized as follows :

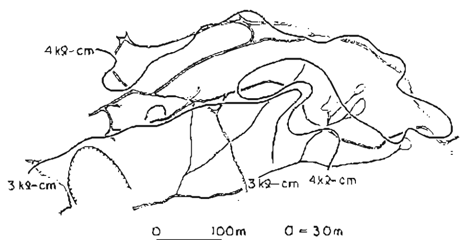

Fig. 12 The distribution map of an apparent resistivity value at a=30, the Tanokura lanslide area

(1) It is possible to detect the discontinued boundary of the underground geological structure qualitatively by vertical exploration.
(2) Though it is impossible to make precise measurements of the depth of the slide surface, it is neverthless confirmed that any soil layer having resistivity values of 1-5 kΩ-cm represents the layer likely to cause a landslide movement.
(3) It is found by horizontal exploration that any area in which the low apparent resistivity values are distributed represents either a possible landslide danger zone, or an area rich in underground water.

3, Examples of application to various landslides

(1) Mikage Landslide Area

This landslide area is located in the outskirts of Kobe City and the landslide took place immediately after heavy rainfall. The geology of this slide area is composed of an alternate layer of sand stone and shale, which is called a group of Kobe layers. The mean angle of inclination is 7° and a sinking zone, 1 meter in width and 1～2 meters in depth, all of a sudden came into existence surrounding this landslide area no sooner than this landslide had occurred. Since then the movement of the soil mass gradually kept going and it began to show a notable action two days after the rainfall. The zone of this slide movement was rather small scale, covering 50x150 meters (Figure 13). The electrical resistivity survey was conducted at the measuring points indicated in Figures 13

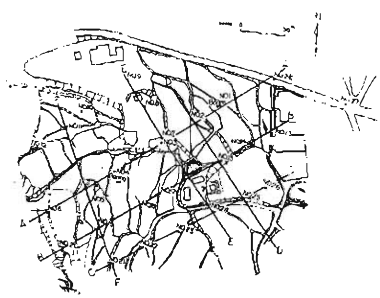

Fig. 13 The measuring locations of resistivity survey of the Mikage landslide area

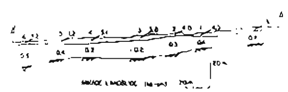

Fig. 14 The resistivile of A-A' section at the Mikage landslide area

in order to find the underground geology roughly. Figure 14 shows the resistivity section-view estimated by vertical exploration. The depth of the slide layer was estimated to be extremely shallow by applying the results obtained from the Tanokura landslide area. According to the boring survey it was known that there was a boundary of shaly clay and shale of a solid nature or sand stone at a distance of 4.2 meters respectively at No. 1 and No. 2. Then it was deducible that the slide should have taken place above the surface of these layers, and the movement of shaly clay was also confirmed on the basis of the results obtained by the internal strain meters [12] which had been buried in boring holes.

It was assumed from further researches that one of the causes giving rise to this landslide must have been the infiltration of surface water and the inflow of underground water into this landslide area from other areas. According to the results of the underground water survey conducted by utilising common salt, it became clear that underground water must have been flowing into this landslide area from the upper part of the slide zone. The analytical results obtained by 'the method of the same electrode span' are shown in Figures 15~16. Judging from these maps, it was observed that the low apparent resistivity values were distributed in the north-

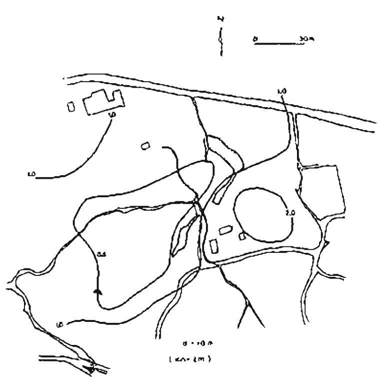

Fig. 15 The distribution map of an apparent resistivity value at a=10m, the Mikage landslide area

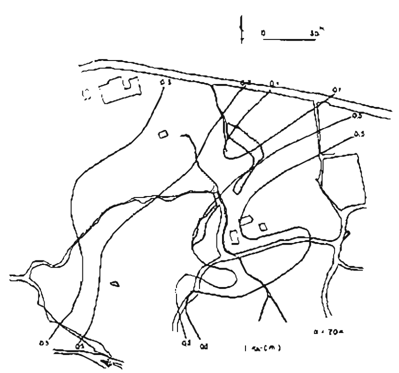

Fig. 16 The distribution map of an apparent resistivity value at a=20m, the Mikage landslide area.

eastern part of this landslide area, the fact of which made us assume that underground water must have been infiltrating from a north-eastern direction or that there must have existed a danger zone in the north-eastern direction of this sinking zone. As a matter of fact the upper part in a north-eastern direction from this sinking zone began to become active again in June 1964 and the extent of the movement kept spreading in an increasing tendency until the dwellers in the upper reaches were forced to sense the danger. Then the Erosion Control Section of Hyogo Prefecture made a drain work project for the underground water by drilling a drain well 10 meters north-east from bore hole No. 1 in February 1966. From this drain well the water began to be taken out at the rate of 120 l/min and at the same time the slide movement was brought to an end.

In this way the depth of the slide layer estimated by the electrical resistivity survey conducted in this landslide area made a good match with the results obtained from the boring survey, and moreover because the resistivity values of this slide layer were found to be 0.9-5.1 kΩ-cm, these finding were just as good as those achieved in the Tanokura landslide area. According to the results analysed of 'the method of the same electrode span', the low apparent resistivity values were found to be concentrated within the landslide area when the electrode span was 10 meters and to be concentrated in the north-eastern part of the landslide area when the electrode span was 20 meters, its exact value being 0.1 kΩ-cm. Consequently, part of this landslide area where the low apparent resistivity values were distributed was regarded as the particular locality which contained underground water in great abundance after taking the results obtained from other kind surveys into due consideration.

(2) Matsunoyama Landslide Area

In the central part of a locality called Matsunoyama in Niigata Prefecture some cracks broke out in November 1962 and later in March 1963 it developed into a landslide covering an immense area nearly as large as 800 ha. in total, partly due to the bad effect of thawing [13].

The geological structure of this landslide area is composed of the later layers of the Tertiary formation, of which composition and order being Shiiya formation, the Upper T. formation, the Lower T. formation and the Matsunoyama tuff layer. These layers are chiefly composed of tuff and mud stone, and an anticlinal structure of doamy type comprising the Matsunoyama tuff layer is formed in the central part of this landslide area.

Judging from the distribution of cracks and the soil mass movement within this landslide area which spread to cover 800 ha., the slide surface of this landslide was estimated to be extremely deep in those days. The crack distribution is shown in Figure 17. Both a boring survey and electrical resistivity survey were conducted to examine the underground geological structure of this extensive landslide area. The target area to be surveyed was decided as to cover the zone from the uppermost part of this slide, i.e. a newly made cliff by the collapsed soil mass, to the central part of the town, Matsunoyama.

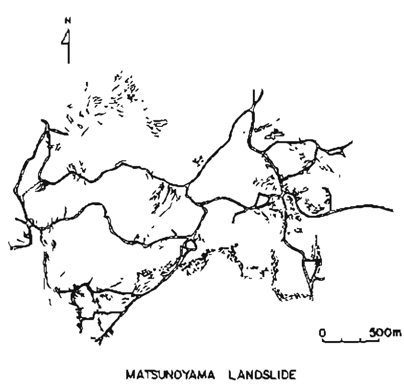

Fig. 17 The distribution map of cracks at the Matsunoyama landslide area

Figure 18 shows the measuring points for the electrical resistivity survey. Figures 19 and 20 show the underground geological structure estimated by the vertical exploration along the principal measuring lines A-A' and B-B'. Judging from these, it could be assumed that there was no one continuious slide surface and that the slide layer seemed to be lying rather at a shallow level.

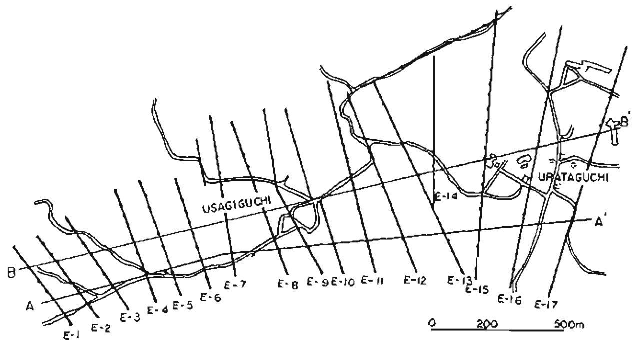

Fig. 18 The measuring locations of the resistivity survey at the Matsunoyama landslide area.

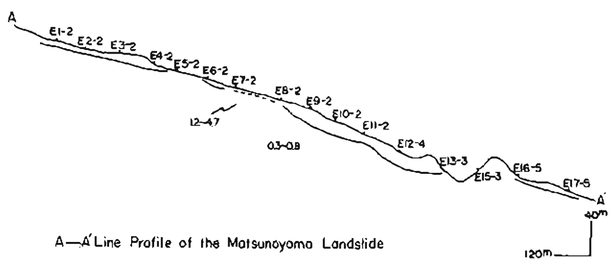

Fig. 19 The profile of A-A' section estimated by resistivity survey, the Matsunoyama landslide area

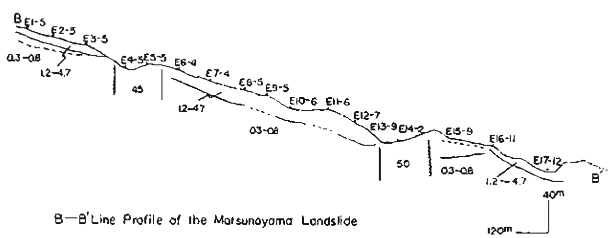

Fig. 20 The profile of B-B' section estimated by resistivity survey, the Matsunoyama landslide area.

The resistivity values of this slide layer were 1.2-4.7 kΩ-cm, which were equivalent to the results obtained in the Tanokura landslide area. Beneath this layer there was a shale layer having resistivity values of 0.3-0.8 kΩ-cm.

According to the geological survey it was belived that there existed dislocated layers in this area under our survey, but as a result of our electrical resistivity survey it was found that many places having a resistivity value of 50 kΩ-cm were detected along the line E-13 - 15, and that such a value could only be accounted for as a result of such dislocation. Figure 21 shows the analytical results obtained by the 'method of the same electrode span'. Figure 22 is the distribution map of those areas that had low apparent resistivity values of less than 1 kΩ-cm at each electrode span. It could be seen from this map that the low apparent resistivity values were concentrated in two separate areas A and B. When the assumption established at the Tanokura landslide area was applied with reference to the areas having low apparent resistivity values, we could reasonably assume that the abundant underground water must have existed in area A, and the fact that underground water was in reality overflowing from a boring hole 10 meters in depth located in area A furnished fine proof of it.

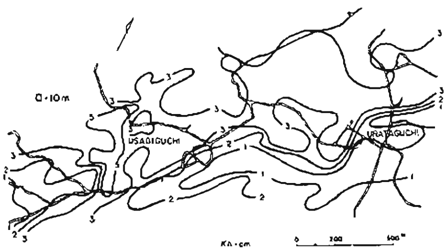

Fig. 21 The distribution map of an apparent resistivity value at a=10m, the Matsunoyama landslide area

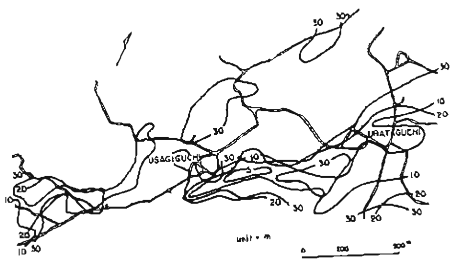

Fig. 22 The distribuution map of the lowest apparent resistivity regions at each electrode span.

In the other hand it was not known at the time when the survey was being undertaken whether zone B had plenty of underground water or exhibited some signs to foreshadow a possible slide movement, but the report made public in 1965 [14] definitely pointed out that zone B contained underground water in great abundane.

(3) Soryo Landslide Area

This landslide area is located in a locality called Soryo in Wajima City in Ishikawa Prefecture and it is recorded that the initial landslide movement began to be activated in the 1900's.[15] The recent slide movement in this area began to become very active after 1962 and a substantial survey was put into effect from 1964. The geology of this area is composed of a breccia loamy clay layer running on top and deposited tuff below it. In addition andesite runs through this strata and this andesite forms what is called "cap rock" by Takano [16] and Nakamura [17] which is one of characteristics of the area. This landslide 800 meters in length and 1,200 meters in width took place, starting from the boundary of the above-mentioned andesite, tuff and mud stone and terminating at the seacoast of the Japan Sea.

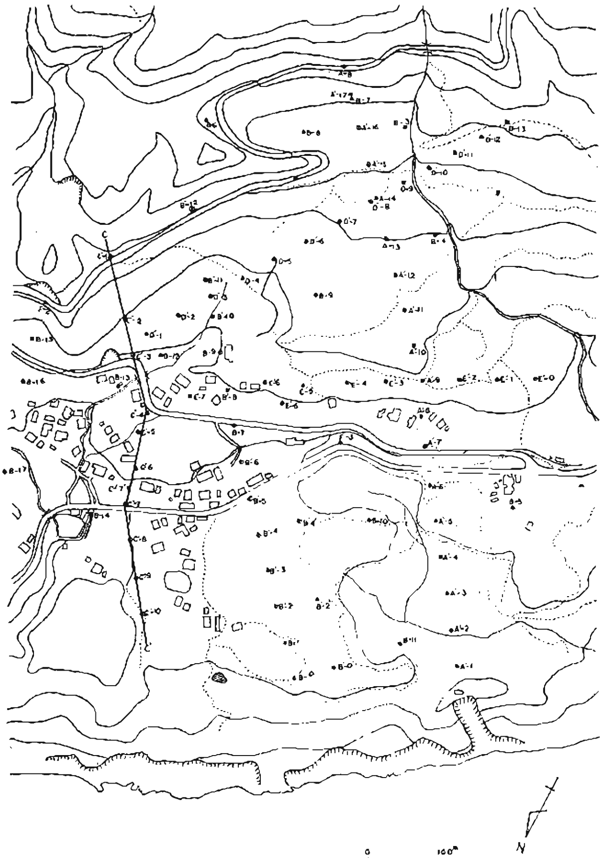

Fig. 23 The measuring locations of resistivity survey and the topography at the Soryo landslide area

The electrical resistivity survey was conducted throughout the whole area in order to examine the underground geological structure. Part of the results of the vertical exploration revealed that underground structure was of three-layer composition as seen in Figure 24. The first layer having resistivity values of 8-20 kΩ-cm was the surface soil layer, the second layer having values of 0.8-4.5kΩ-cm could be assumed to be the slide layer and the third layer having values of less than 0.1 kΩ-cm could be taken for the bed rock. When th is three-layer composition was checked against the results obtained by the boring survey, it was found that the first layer corresponded to loamy breccia, the second layer to loamy clay and the third layer to mud stone or tuff.

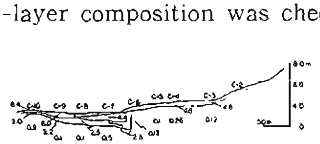

Fig. 24 The profile of C line estimated by resistivity survey at the Soryo landslide area

In addition Figure 25 shows the distribution of the low apparent resistivity values less than 1 kΩ-cm in all cases for each electrode span (5, 10, 20, 30 meters). Judging from Figure 25, the distribution of the low apparent resistivity values was seen to be concentrated in three areas A, B and C, and it could be reasonably assumed from the electrical resistivity aspect that they were rather homogeneous layers down to a certain depth. In area B stood a great number of houses, in one of which cracks were observed at the time when the survey was being made, but no other distinct chages were observed on the ground surface elsewhere. Consequently, it was a justifiable guess to say, based on our experimental survey ot the Tanokura landslide, that area B was in danger of a possible future landslide movement.

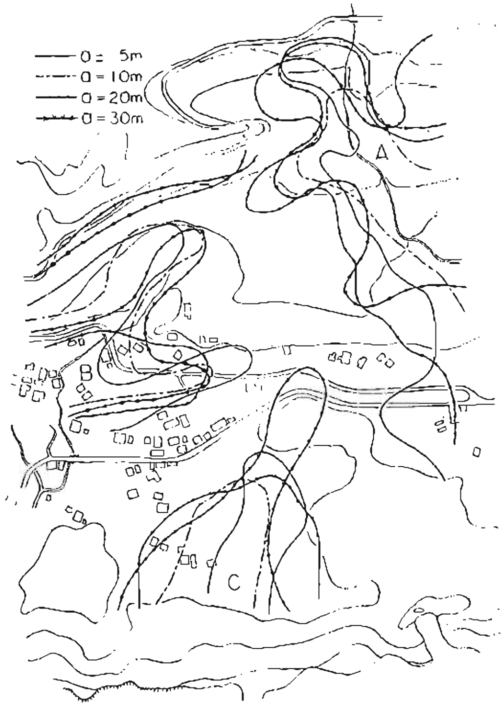

Fig. 25 The distribution map of the lowest apparent resistivity region at each electrode span.

As for area A, because some movement was observed when our survey was being carried out it was concluded that this area was a locality containing underground water in great abundance. As for area B, it was reported in July 1967 [18] that no small damage had been caused to many houses in area B as shown in Figure 26, the fact of which again

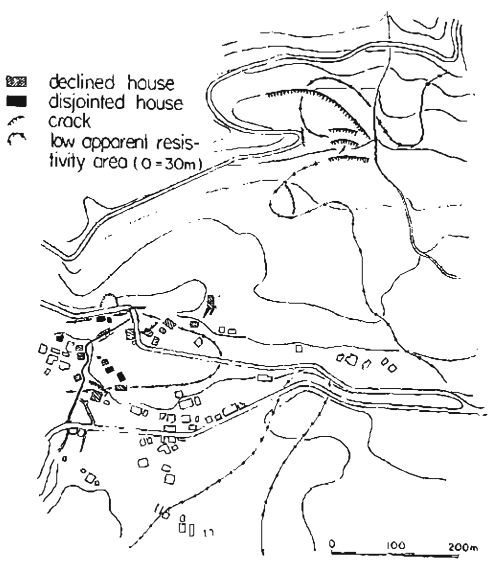

Fig. 26 The location map of cracks and the distribution map of the lowest apparent resistivity value regions at each electrode span, the Soryo landslide area.

made us realise the significance of the electrical resistivity method.

(4) Ogoto Landslide Area

This landslide area is located in a town called Ogoto in Shiga Prefecture. This landslide took place on 21st June 1966. A marked movement was kept going for a period of one and a half months but at present practically no movement is observable because of effective preventive work (Figure 27). The geology is partially composed of breccia of lake-making and principally of a clayey layer which is called an Old Biwako formation.

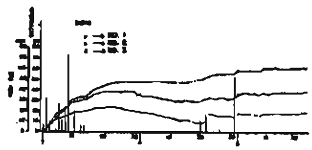

Fig. 27 The surface displacement graphs recordedby an extensometer in 1967, the Kushibayashi landslide area.

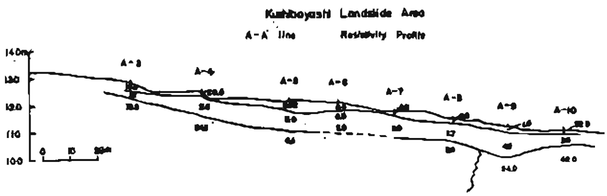

Fig. 28 The profile estimated by resistivity survey at A-A′ section, the Kushibayashi landslide area.

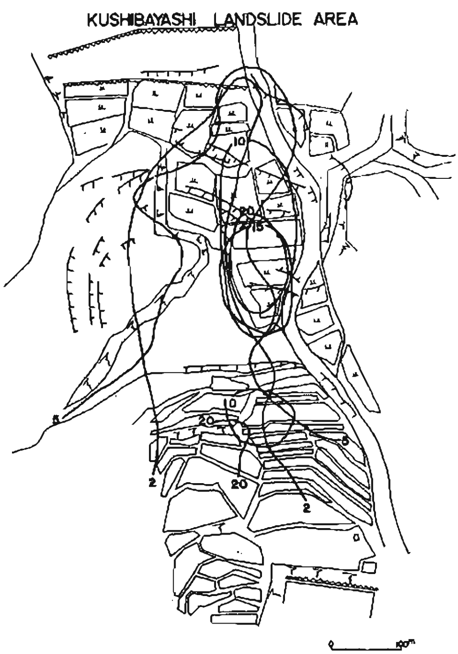

Fig. 29 The distribution map of the lowest apparent resistivity value regions at each electrode span, the Kushibayashi landslide area.

The electrical resistivity survey was conducted two weeks after the occurrence of the slide. The results of vertical exploration are shown in Figure 28. The resistivity values of this slide layer could be estimated to be 1.2-4.2 kΩ-cm from Figure 28 (with the exception of 0.3 kΩ-cm at only one place), which made a good parallel with the results obtained in the Tanokura landslide area. The resistivity values of the clay layer which formed the bed rock indicated 6.4-24 kΩ-cm and the sand layer which was interposed irregularly indicated 35-42 kΩ-cm.

Figure 29 shows the distribution of the low apparent resistivity values less than 3 kΩ-cm at each electrode span, which proved a close-up of the existence of two separate areas. Because the above-mentioned values represented their state of resistivity after the slide took place, it was not acceptable to say that those two areas represented 'the danger zone' for possible future landslides and we were led to conclude that those areas must be localities with plenty of underground water. In fact a draining well was drilled in area A in January 1967 and underground water flowing into that well has been overflowing ever since that time. This was another fine demonstration proving the significance of the use of the electrical resistivity method applied to landslide surveys.

(5) Choja Landslide Area

This area is located in Kochi Prefecture and its history is very old, the slide movement being accustomed to break out intermittently since 1885 [19]. Heavy rainfall recently actuated its slide movement to become acive in October 1963 and researches of various types were started after 1964. This landslide was characterized by its occurrence in a fractured zone running across the island of Shikoku almost from east to west, which should be particualarly noted as "a landslide in a fractured zone". [20] Since it so happened to be the first case, as far as the present writer knew, where the electrical resistivity method was ever applied to a landslide that had broken out in an area within a fractured zone, a great deal of interest was aroused in finding out the results achieved by the electrical resistivity method. In this connection the present writer will quote what Yamaguchi [21] and his colleagues achieved in the way of surveys and analysis.

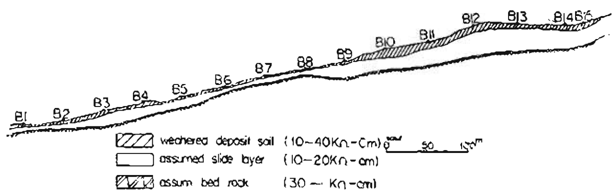

Fig. 30 The profile estimated by resistivity survey at B line, the Chōja landslide area.

Judging from the results of vertical exploration, this area is of a three-layer composition as shown in Figure 30, with the lying order of a weathered sedimentary layer on top, clayey serpentine in the middle and fresh serpentine at the bottom, of which the resistivity values run respectively as follows: 10-40 kΩ-cm for the first layer, 10-20 kΩ-cm for the second layer and over 30 kΩ-cm for the bottom layer. Judging from the distribution of the low apparent resistivity values, it was found that those values were concentrated in certain places (see Figure 31). According to Tochigi [22], the main stream of the slide movement of this landslide area was moving in the direction pointed by arrows in Figure 31, and the main body of the moving soil mass proved to make a fairly good match with the low apparent resistivity zone. Consequently, it could be assumed, even in connection with the landslide area characterized by a fractured zone, that the distribution of the low apparent resistivity values did have a very close relationships with landslide activity.

(6) Kebioka Landslide area

This landslide area is located in a town called Muraoka in Hyogo Prefecture, covering a total area of 5 ha.. The geology of this area is composed of an alternate layer of tuff, sand stone and conglometrate, all belonging to the later layers of Tertiary formation, which is called Muraoka formation, and a layer of

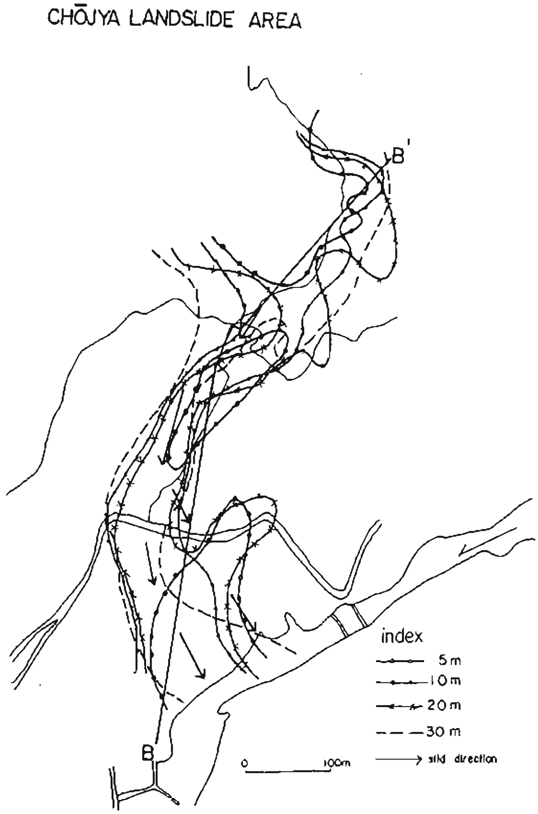

Fig. 31 The distribution map of the lowest apparent resistivity value regions at each electrode span, the Chōja landslide area (arrow marks show slide direction)

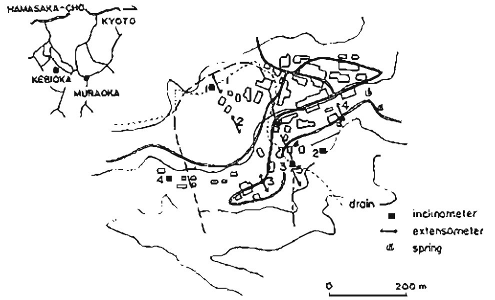

Fig. 32 The topography and measuring locations of resistivity survey, the Kebioka landslide area.

basalt runs across it in the close vicinity of the upper part of this landslide area.[23]

The rate of this slide movement was extremely slow and practically nothing was known about the time of its occurrence and the total volume of the moved soil mass in a year, not to speak of any sign of cracks which might serve to furnish proof of a landslide. The electrical resistivity survey was conducted at this landslide area in July

1963 in order to determine the underground geological structure. For topographical reasons we could provide no morethan 11 measuring points for the electrical resistivity survey (Figure 32), and the analysis on the basis of ' the method of the same electrode span ' could not be conducted. Therefore, all apparent resistivity values (ρ-a) obtained at each measuring point and the respective electrode spans were put down on the logarithmic graph paper and the ρ-a-curves were put under our examination (Figure 33). The curves, namely A 1-6, B 1-3 and A7, showed some difference in their shapes. On the basis of this difference in the shape of the ρ-a curves, this landslide area was sub-divided into the two separate areas A and B after taking the topographical factors into due consideration. Then we presumed that if a landslide movement was to take place in future, it would be most likely to occur in the area of A 1-6.

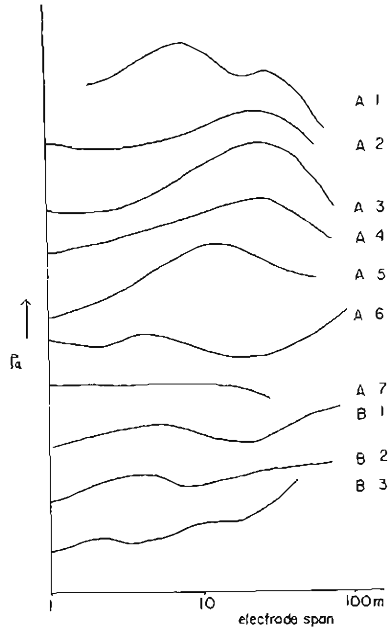

Fig. 33 The apparent resistivity —- electrode span curves which were obtained by four electrodes method at the Kebioka landslide area.

Generally speaking, there is at present no difinite rule to prescribe where to install measuring instruments. The place to set them up is commonly decided on the basis of the surveyor's past experience, after treading the area from end to end. However, the present writer decided to make it a fundamental principle to set up the neccessary apparatus on the basis of the results obtained from the electrical resistivity survey. Putting it in an other way, the dashedline indicated in Figure 32 suggested the area in which the slide movement could be presupposed with the highest possibility, and within such an area 4 sets of extensometers and 2 sets of inclinometers were buried. At the same time 1 set of extensometers and 2 sets of inclinometers were also buried in an other area where no landslide movement could be anticipated so that the two kinds of results to be obtained from the two kinds of areas could be compared. Figure 34 shows the results observed by extensometers, from which it was brought to light that the mechanism of the landslide movement was not brought about by a push from the upper part but by a pull from the lower part.

Thus it was confirmed as seen in this example that the electrical resistivity method could provide the planning of the survey with such fundemental data. However, it was later found by further observation that the depth of the slide surface could be assumed to be 70 meters. Therefore we were led to the conclusion that there would be no practicable preventive counter-measures to be desighed from the ground surface. Thus, ditch-making to prevent surface water from infiltrating into this landslide area and drilling of a draining well to take underground water out were put into effect.

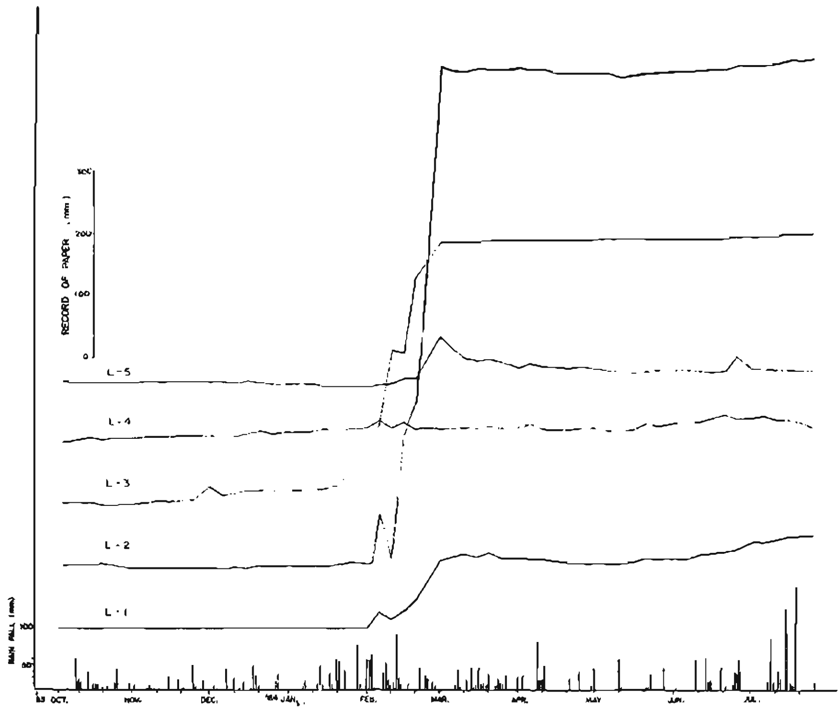

Fig. 34 The surface displacement graphs recorded by extensometers, the Kebioka landslide area.

4. Conclusion

If it is essential to analyse the underground geological structure in making any landslide survey, then the problem is what sort of means should be used for such a survey in order to obtain the necessary information most promptly and exactly. The present writer has been conducting surveys in various areas utilising the avantages of the electrical resistivity method to theofullest extent, such as (1) the low cost of survey expense, (2) achieving results in the shortest possible period of time and (3) finding, though roughly, the geological underground structure, and as a result I could gain first-hand knowledge about the use and limitation of the electrical resistivity method.

As to the underground geological structure survey by vertical exploration, the depth far down to any bed rock was likely to be measured somewhat deeper than the actual depth, but I could roughly find the general nature of the underground structure similar to that which actually existed. Consequently, if the underground geological structure can be examined by the electrical resistivity method, we can then foretell and plan in advance where and how deep boring will be required.

As to the slide surface, it has been brought to light that slide movement in the area of the Tertiary formation is caused within the range of resistivity values of 0.8-5.2 kΩ-cm. However, it must be understood in this case that it is not one single slide layer that moves when a landslide takes place, but that any other part or parts within one slide surface can move under any predisposing conditions.

It can be presupposed that any area having low apparent resistivity values according to the distribution chart prepared by 'the method of the same electrode span' is either (1) a locality containing underground water in great abundance, or (2) a locality having a high possibility of a possible landslide movement taking place in the future. The apparent resistivity values in the landslide area of the Tertiary formation are found to be 2-0.1 kΩ-cm. However, we have not yet been able to find what can possibly be meant in connection with a certain landslide area by the distribution map of the low apparent resistivity values observed by 'the method of the same electrode span'. Nevertheless, it can be regarded that any area in which the slide movement was once active, as seen in the examples of the Ogoto area, A and B of the Matsunoyama and Mikage landslide areas, contains underground water in great abundance on the one hand and that any area in which cracks didn't develop too much and the movement was rather mild, as seen in the examples of the Soryo or Tanokura landslide areas, has a high possibility of a severer slide movement being activated in the future on the other. In this way the distribution map of the low resistivity values can be interpreted according to twofold meanings. Consequently, if the movement of any area in which the low apparent resistivity values are concentrated can be examined, then a possible landslide movement in the future can be anticipated to a certain extent by the electrical resistivity method.

If the results of the Choja landslide area surveyed, which is an example of a landslide of the fractured zone type, are analysed in condomity with the forementioned category, it can be assumed that this area is rich in underground water, and in fact it is found that the general direction of the soil mass movement was consistent with what actually happened in reality. Therefore, as far as a landslide area of fractured zone type is concerned, it appears that what the low apparent resistivity values mean is different from what they would in the area of the Tertiary zone type of landslide.

In this way, whenever any landslide study is to be pursued, the electrical resistivity survey should by all means be conducted prior to all other kinds of surveys or researches, excepting topographical and geological surveys.

The next step is to make analyses on the basis of a variety of researches, such as vertical exploration, horizontal exploration (the method of the same electrode span), in order to examine or determine the continuity of the underground geological structure, the depth of a slide layer and the distribution map of the low apparent resistivity values. Then it will not only become possible by going through such procedures to select the most adequate location where varied kinds of measuring instruments for the geophysical survey are to be installed on the basis of the analytical results thus obtained, but also at the same time such analyses will enable us to plan efficient landslide preventive work on the basis of the reasonable supposition of abundant underground water in any area in which the landslide movement is active or the low apparent resistivity values are concentrated.

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